Future Dark Cosmology Constraints with Weak Gravitational Lensing

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The Plan

- Observable consequences of dark energy or modified gravity.
- Model-independent, robust answers from WL
- Example forecasts

The acceleration question(s)

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

1. Is there a cosmological constant?

2. Is the Universe is dominated by a substance with negative pressure: *"dark energy"*? What is *w(z)*?

$$w \equiv P/\rho < -\frac{1}{3}$$

3. Is GR correct? Does alteration to Friedmann equation come with changes or scale-dependence to Poisson eqn, light-deflection formula (*e.g.* anisotropic stress)?

The curvature question:

In the Robertson-Walker metric:

$$ds^2 = c^2dt^2 + a^2(t)\left[d\chi^2 + S_k^2(\chi)\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

$$D(\chi) \equiv S_k(\chi) = \begin{cases} \chi_0 \sin(\chi/\chi_0) & k=1 \\ \chi & k=0 \\ \chi_0 \sinh(\chi/\chi_0) & k=-1 \end{cases}$$

Flatness is the *sine qua non* of inflation: $\chi_0 \gg 1$

Curvature fluctuations are small and roughly scale-invariant, so within our horizon:

$$\omega_k \equiv \Omega_k h^2 = -k/\chi_0^2 \approx 10^{-5}$$

How well can we test this?

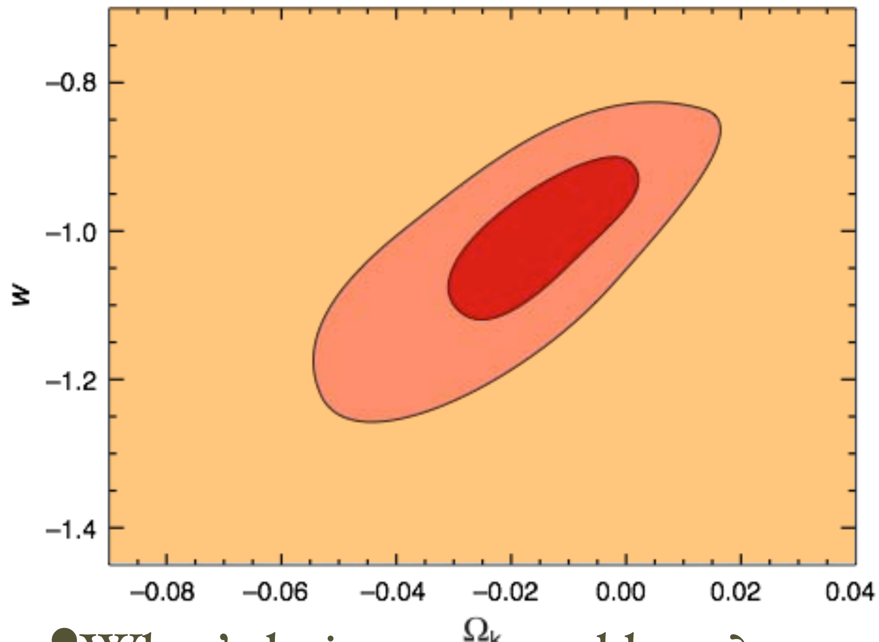
A test of the anthropic principle?

(Distances in units of c/H_{100}=2998 Mpc; $h(z)$ is $H(z)$ in units of H_{100})

The structure evolution question:

- Does the dark-matter-halo paradigm correctly describe the formation of galaxies and clusters?
- In this talk I will concentrate on the previous cosmological questions, but there already extensive data on the characteristics of dark halos from lensing (*e.g.* Mandelbaum et al; Sheldon et al.)
- *cf.* talks by K. Kuijken, D. Clowe for more on dark matter issues

Didn't WMAP already answer these questions?



From WMAP3: Curvature/DE constraints combining WMAP3, 2dFGRS + SDSS galaxies, supernovae.

- What's being assumed here?
  - Universe is described by Robertson-Walker metric
  - General Relativity describes dynamics:
    - Friedmann Equation holds
    - Growth of structure follows usual equation
  - Dark energy behaves like fluid with constant equation of state (e.g. is negligible at recombination epoch).
  - Adiabatic fluctuations

The distance observable for dark energy

Minimal Assumption: RW metric

$$ds^2 = c^2 dt^2 + a^2(t)\left[d\chi^2 + S_k^2(\chi)\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

Gives *comoving radial distance*:

$$\chi(z) = \int_{t_z}^{t_0} \frac{c\,dt}{a} = \int_0^z \frac{dz'}{h(z')}$$

Next assumption: GR's Friedmann equation:

$$h^2(z) \equiv (\dot{a}/a)^2 = \omega_m(1+z)^3 + \omega_r(1+z)^4 + \omega_k(1+z)^2 + \omega_X f_X(z)$$

Measurable manifestations of component X are *h(z)* and the *transverse comoving distance* *D(z)*:

$$D = S_k(\chi) \approx \chi(1 - \omega_k \chi^2/6)$$

$$\chi(z) \stackrel{\omega_k}{\Longleftrightarrow} D(z)$$

The growth observable for dark energy:

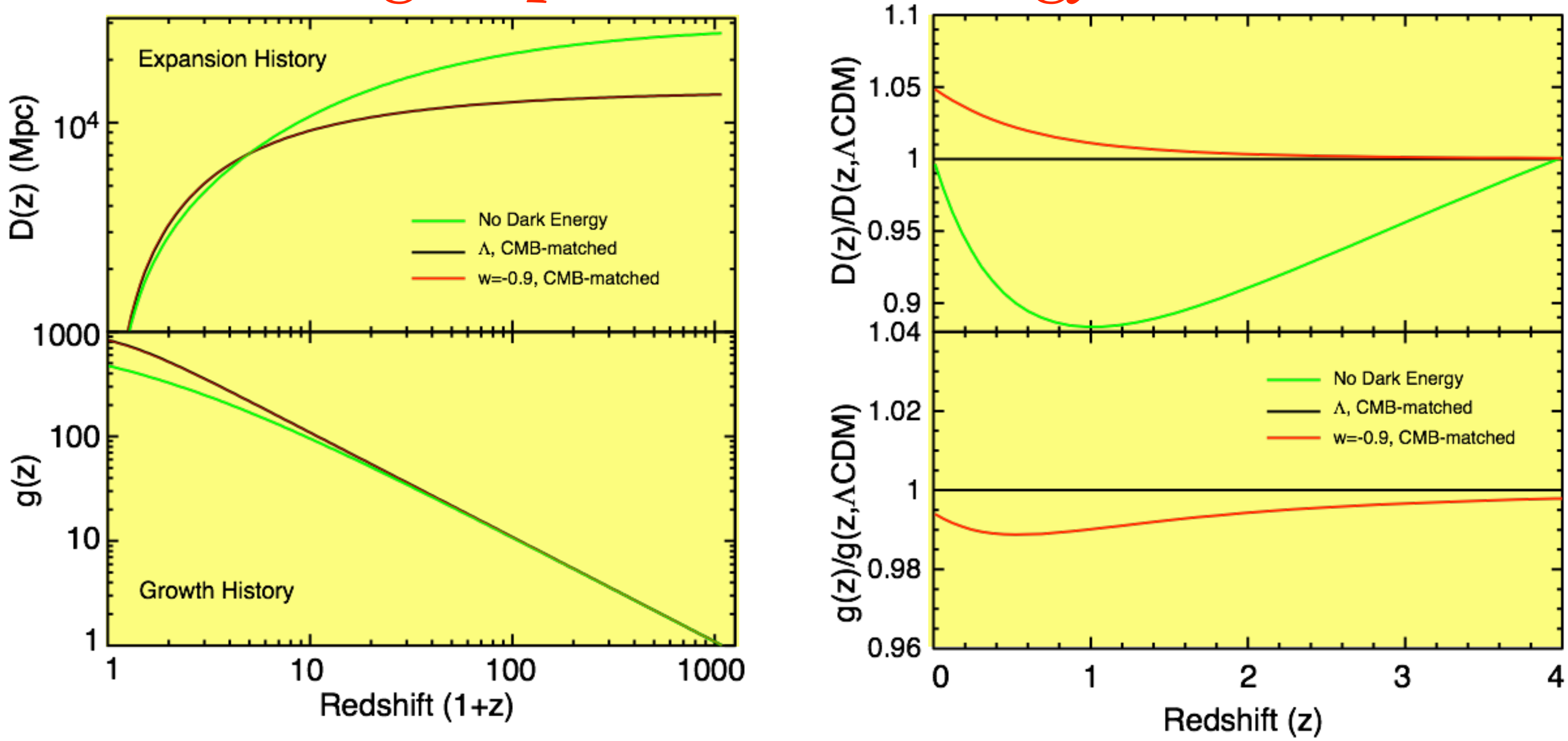
- **If** mass follows geodesics of perturbed RW metric
- **and** Poisson equation (GR) correctly describes metric perturbations
- **and** non-relativistic matter sources all metric fluctuations
- then we have a firm prediction for growth of structure in linear regime:

$$\frac{\delta\rho(\mathbf{x},t)}{\bar{\rho}(t)} = g(t)\delta(\mathbf{x}) \qquad \ddot{g} + 2h\dot{g} = \frac{3\omega_m}{2a^3}g$$

- ...and non-linear structure is also predictable.

Simultaneous determination of *D(z)* and *g(z)* serves as consistency check of GR. Is acceleration a failure of GR instead of a new mass-energy component?

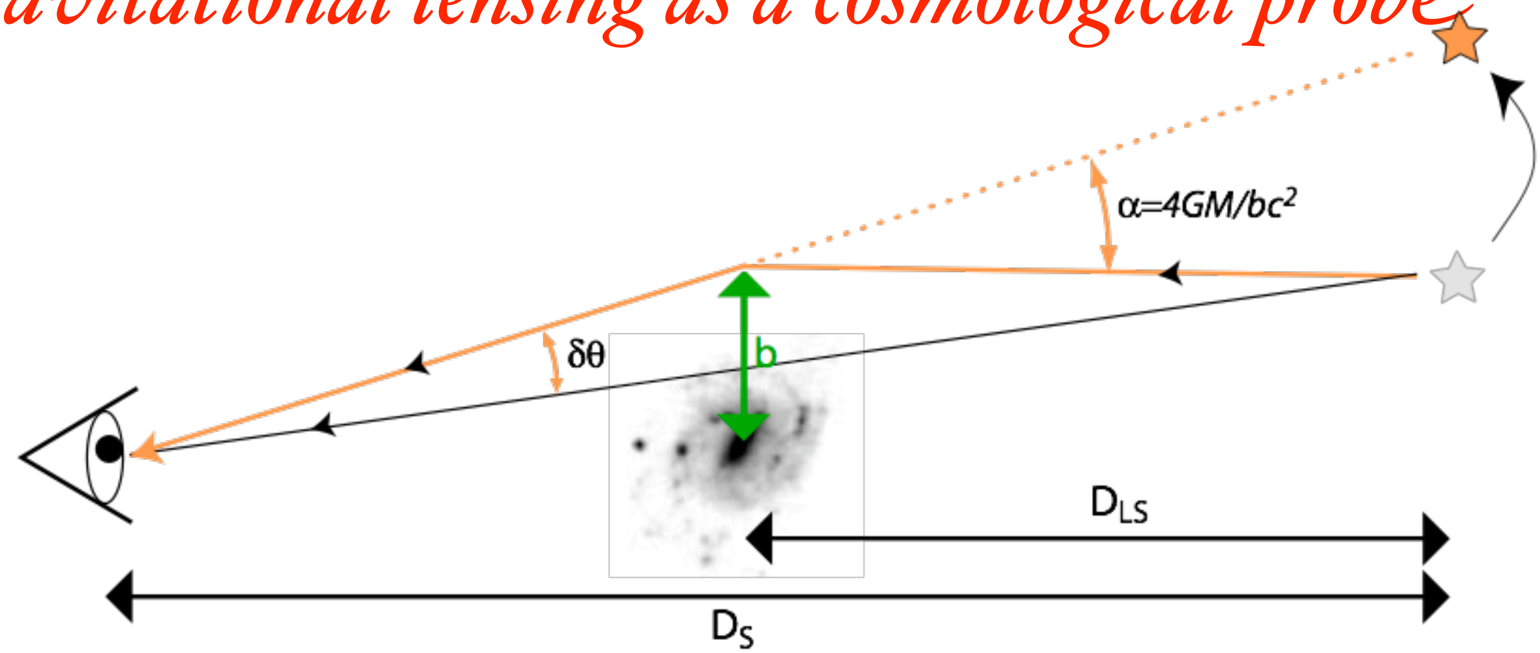
The challenge to precision cosmology



Discovery of acceleration (distinguish from open Universe) required ~10% determinations of distance

Study of dark energy requires sub-percent accuracy in distance and growth.

Gravitational lensing as a cosmological probe



$$\delta\theta = \frac{4GM}{bc^2}\,\frac{D_{LS}}{D_S}$$

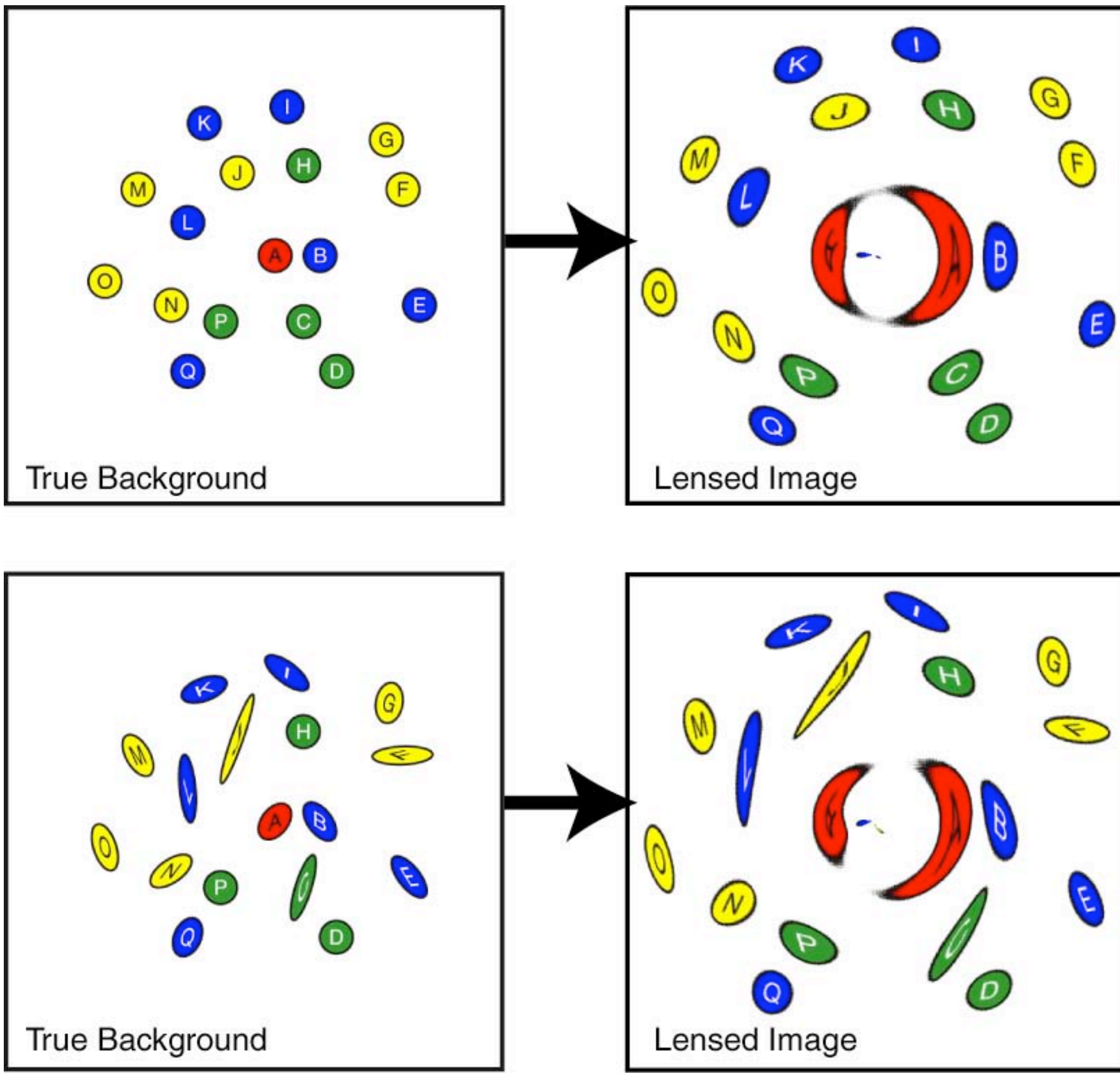
We observe this deflection angle (more precisely, gradients of the deflection angle).

Cosmology changes growth rate of mass structures in the Universe.

Cosmology changes the geometric distance factors.

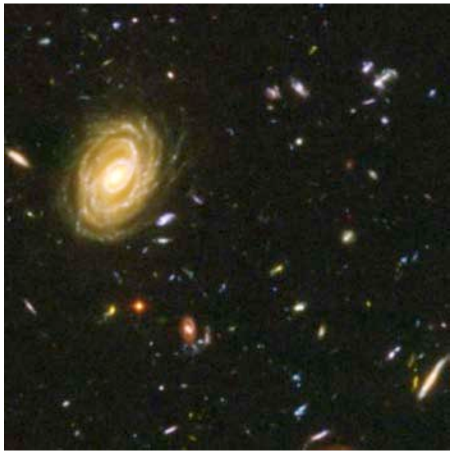
(alterations to Poisson or deflection formulae manifest here too)

Weak gravitational lensing



- Deflection angles are not generally observable since lensing mass cannot be removed!
- In **weak** gravitational lensing, we instead measure the **gradients** of the deflection angle as distortions to the shapes of galaxies.
- The intrinsic variation of galaxy shapes then becomes a source of noise which averages away as $\sqrt{N}$
- Cosmic signal is ~0.02; shape noise is $0.25/\sqrt{N}$; N~1e9!

Choose your background photon source:

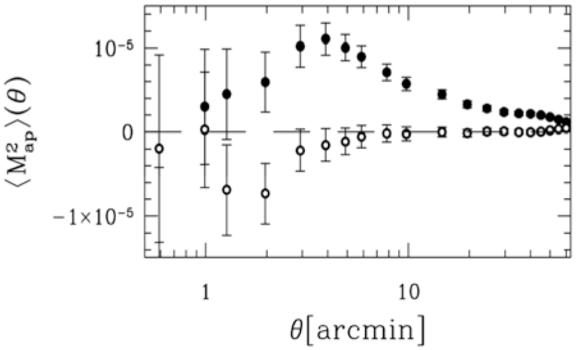


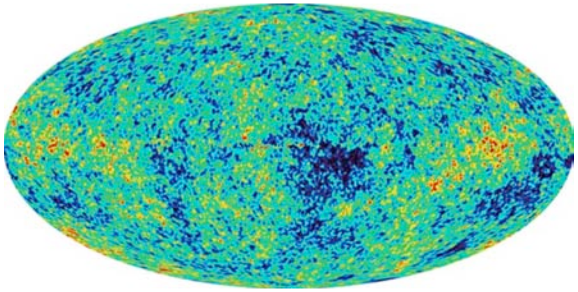
Faint background galaxies:

Use visible/NIR imaging to determine shapes.

Photometric redshifts.

Hoekstra et al 2006:





Photons from the CMB:

Use mm-wave high-resolution imaging of CMB.

All sources at z=1088.

(lensing not yet detected)

21-cm photons:

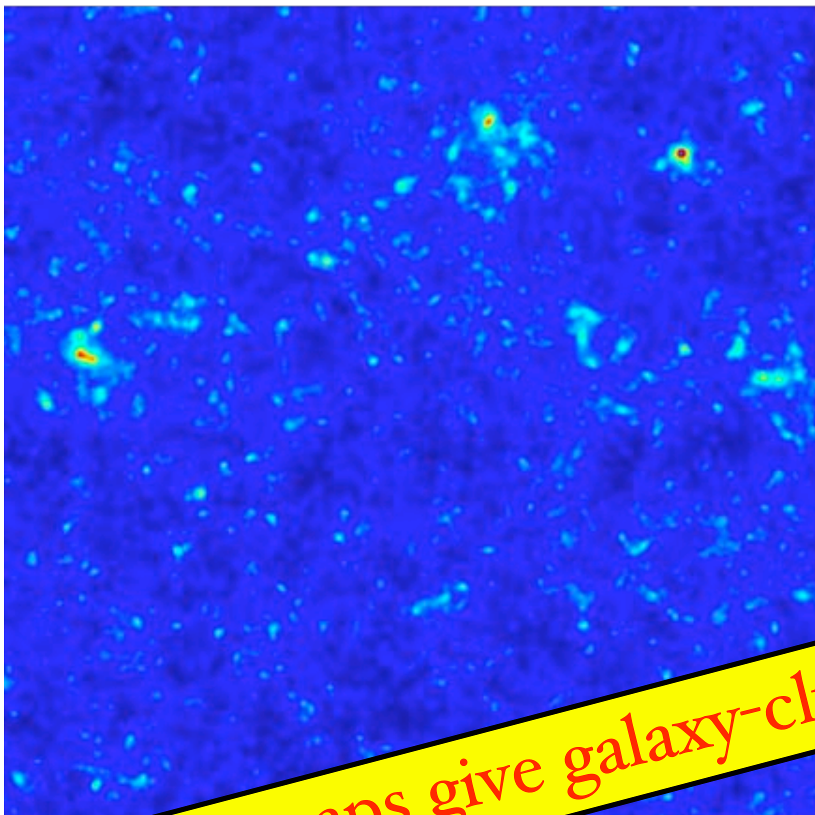
Use the proposed Square Kilometer Array (SKA).

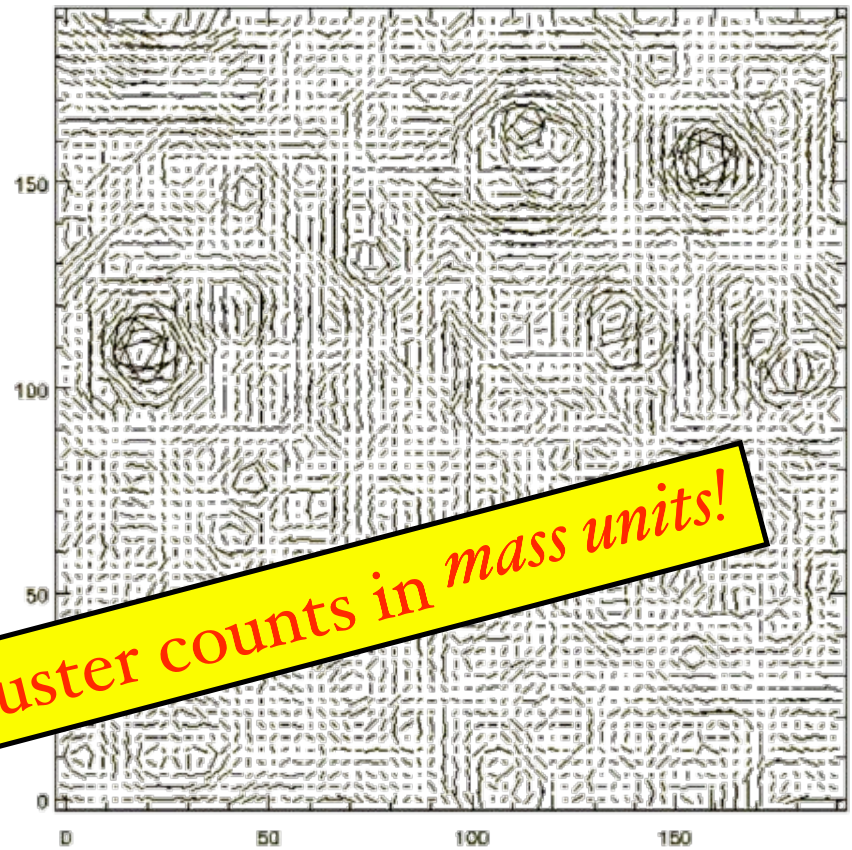
Sources are neutral H in regular galaxies at z<2, or the neutral Universe at z>6.

(lensing not yet detected)

Weak Lensing as a View of Dark Matter

Noiseless shear field in 3 degree square patch of sky: 2% RMS shear





Shear maps give galaxy-cluster counts in *mass units!*

B. Jain

Limitations to Weak Lensing Measurements

- Lensing is detected as breaking of a symmetry in distribution of a background property; intrinsic variance of the background is "shape noise" source. *(increase source density)*

- WL statistics involving variances (power/bispectra) have finite-sample limits. *(increase survey area & depth)*

- Theoretical predictions have finite accuracy, esp. mass structure on small scales (<100 kpc) *(do not infer dark-energy properties from small-scale mass spectrum)*

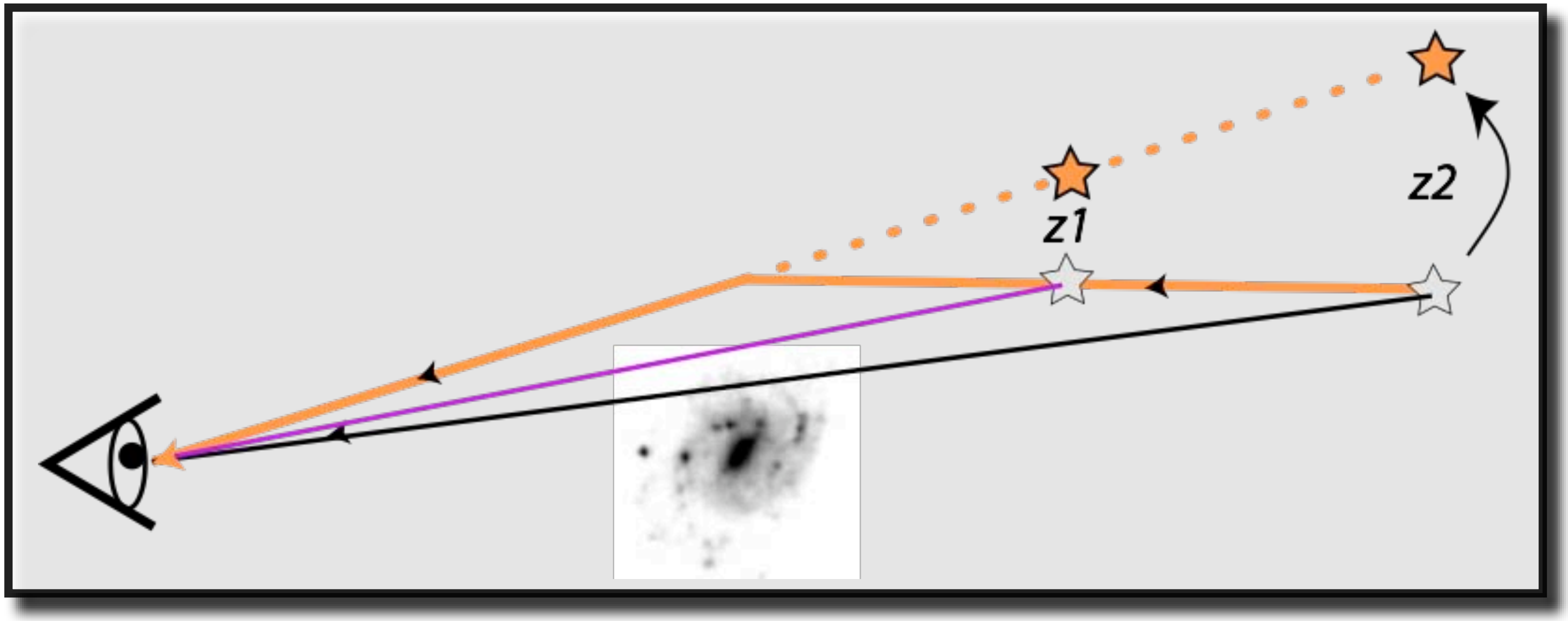
- Systematic measurements errors on shear/redshift *(experimental design & techniques)*

WL pattern depends upon many physical effects:

- Good stuff:
  - Expansion history *D(z)*
  - Growth history *g(z)*.
  - Curvature
  - Change to Poisson equation or light-deflection formula
- *Bad stuff:*
  - Galaxy alignments due to atmospheric/optical distortions ("additive shear systematics"). Fix using stellar images!
  - Flaws in techniques to extract shears ("multiplicative/calibration shear errors")
  - Galaxy alignments due to tidal gravity, etc. ("intrinsic alignments")
  - Mis-assignment of source redshifts

Is this hopelessly complicated?
Gravitational lensing offers such a rich dataset that it is possible to test each of these assumptions individually, *plus* internal tests for most systematic errors!

Isolating the distance variables (Jain & Taylor):



Ratio of deflection angles:

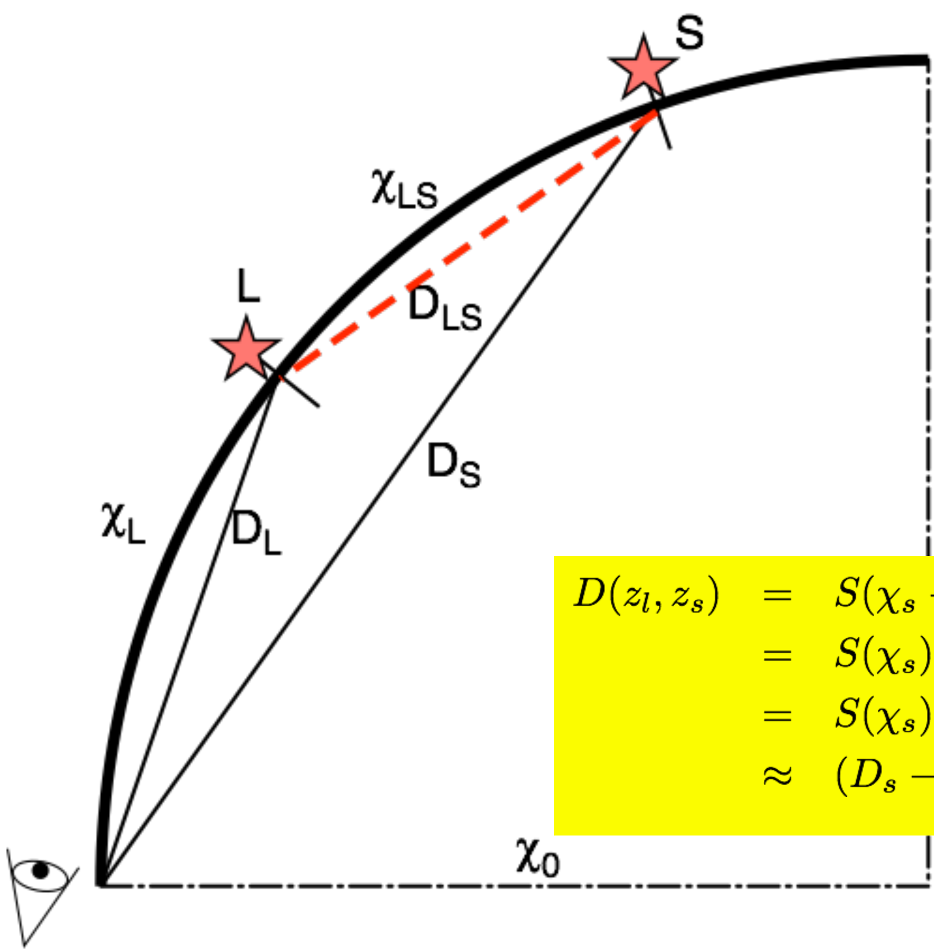
$$\frac{\delta\theta_1}{\delta\theta_2} = \frac{\left(\frac{D_{LS}}{D_S}\right)_1}{\left(\frac{D_{LS}}{D_S}\right)_2}$$

is independent of mass structure, Poisson/GR:

...just RW and expansion history

Lensing as geometric curvature test:

Uniquely among cosmological measurements, lensing signal (deflection) measures chords that do *not* originate at observer.



Triangles = curvature!

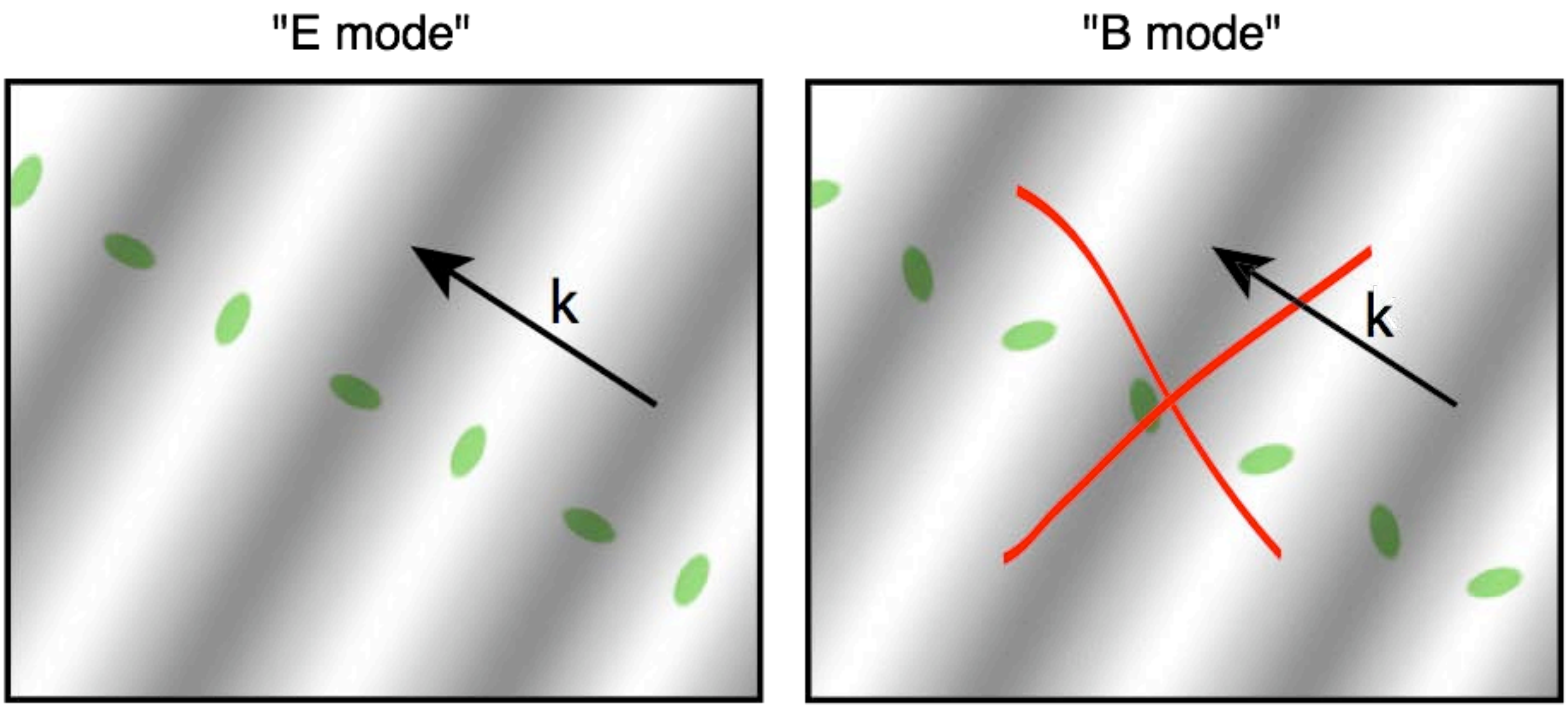
$$
\begin{aligned}
D(z_l, z_s) &= S(\chi_s - \chi_l) \\
&= S(\chi_s)C(\chi_l) - S(\chi_l)C(\chi_s) \\
&= S(\chi_s)[1 + \omega_k S^2(\chi_l)/2] - S(\chi_l)[1 + \omega_k S^2(\chi_s)/2] + O(\omega_k^2) \\
&\approx (D_s - D_l)(1 - \omega_k D_s D_l/2)
\end{aligned}
$$

WL has many observable quantities

- Shear-shear power spectrum (1991)
- Power in non-linear regimes (1997)
- With source-redshift information: shear-shear cross-spectra (1999) for every *pair* of z bins
- Peaks in shear field are cluster counts (~2001)
- Bispectra (2002): non-Gaussian information
- Galaxy-shear cross-spectra (2003)

Weak lensing sky is very rich with information. Many independent statistics with distinct dependence on dark energy. This makes WL capable of simultaneous solution for dark energy, GR modifications, and its own systematic errors!

Weak lensing in Fourier space



Foreground mass sinusoid produces ellipticity pattern at the same k-vector

Lensing cannot produce ellipticity pattern at 45 degrees to k-vector

Extremely simple relation between power spectrum of WL and power spectrum of matter. Plus a built-in null test.

Robustness of lensing cosmology

Change in expansion history at some z affects these

Change in growth or bias at some z affects

Intrinsic alignments appear here

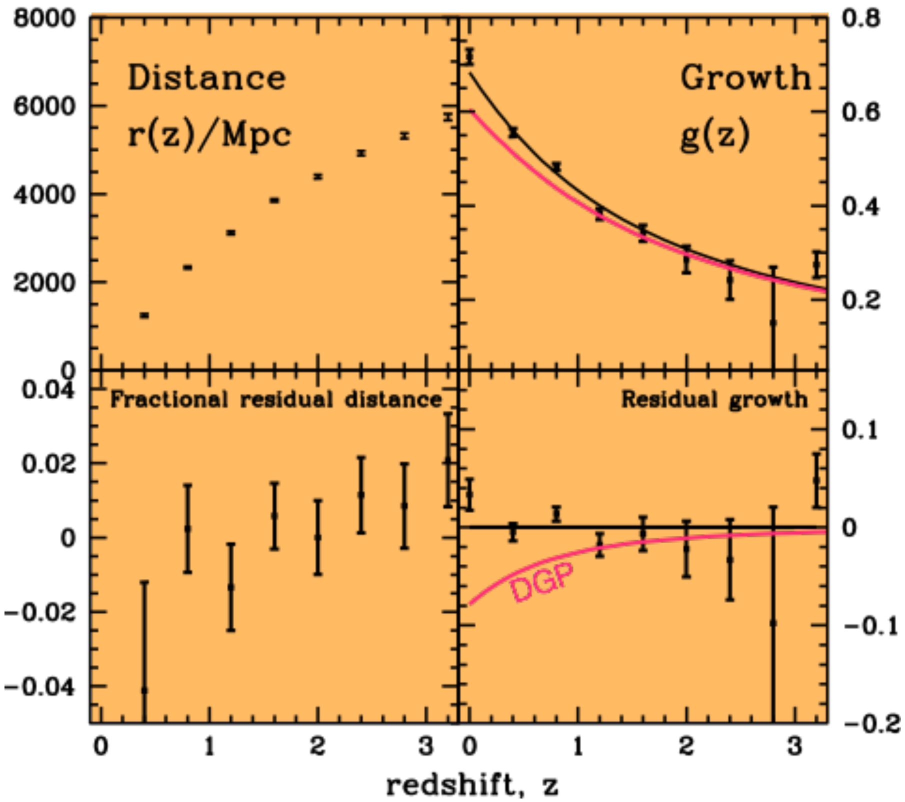
Error in calibration at some z affects

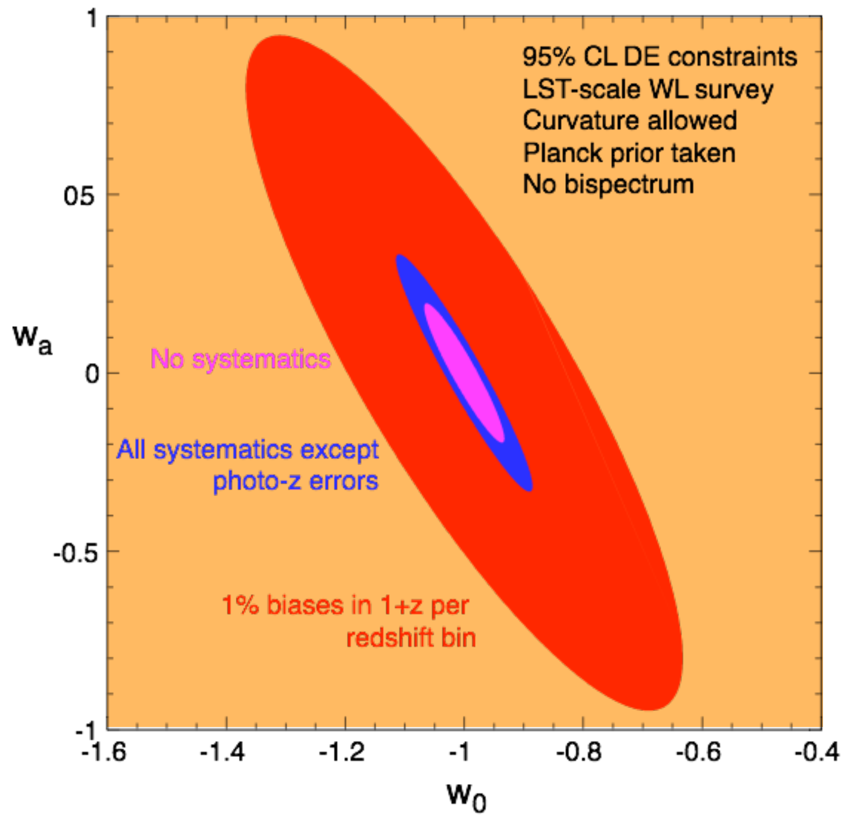
Curvature affects

$$\begin{pmatrix} \text{shear}_1 \\ \text{shear}_2 \\ \text{shear}_3 \\ \vdots \\ \text{shear}_n \end{pmatrix} = \begin{pmatrix} 0 & A_{12} & A_{13} & \cdots & A_{1n} \\ 0 & 0 & A_{23} & & A_{2n} \\ 0 & 0 & 0 & & A_{3n} \\ \vdots & & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{pmatrix} \times \begin{pmatrix} \text{mass}_1 \\ \text{mass}_2 \\ \text{mass}_3 \\ \vdots \\ \text{mass}_n \end{pmatrix}$$

$$A_{ij} = (1 - D_i/D_j)\,(1 - \omega_k D_i D_j/2) \qquad (i < j)$$

WL statistical richness makes it broad & robust





Power spectrum only,
no systematic errors.
20,000 square-degree ground survey

Knox, Song, & Tyson (2005)

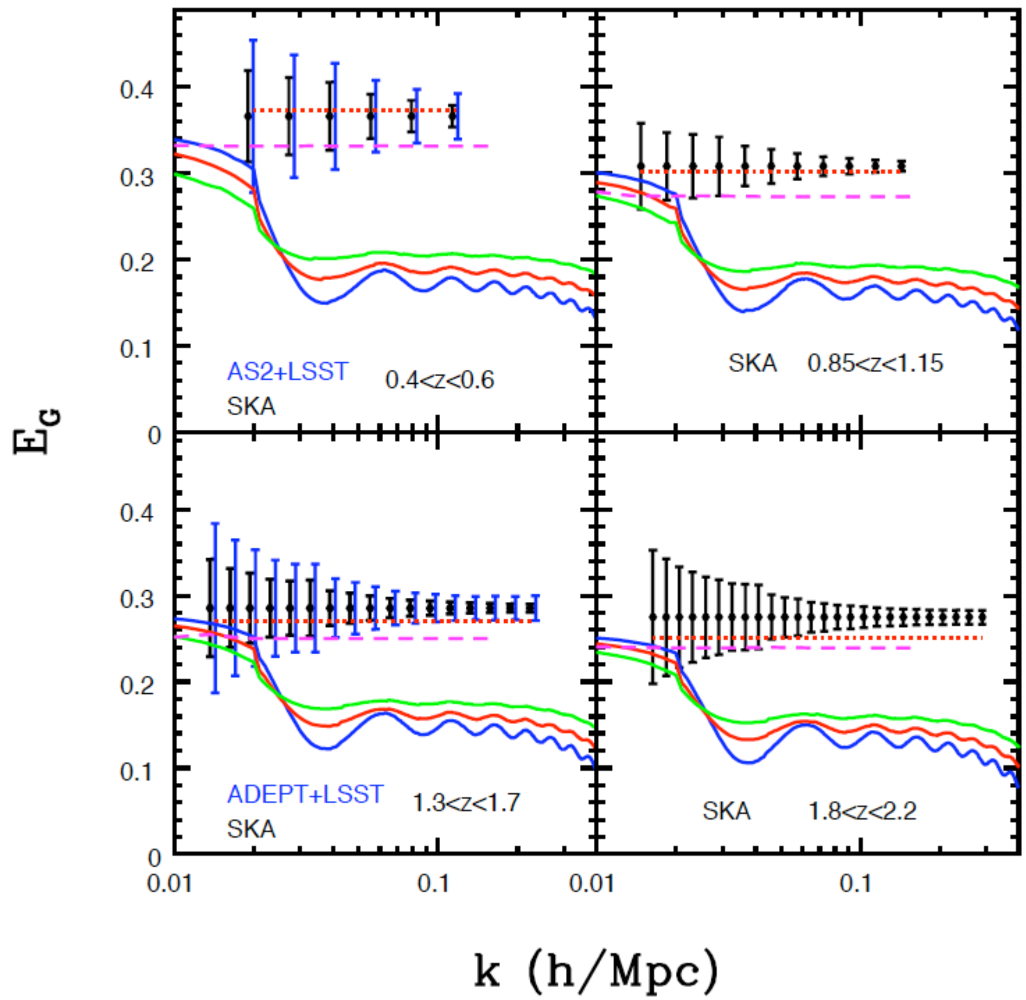
Plus: "guaranteed" neutrino-mass detection (Abazajian; Song & Knox)

Example Test of General Relativity

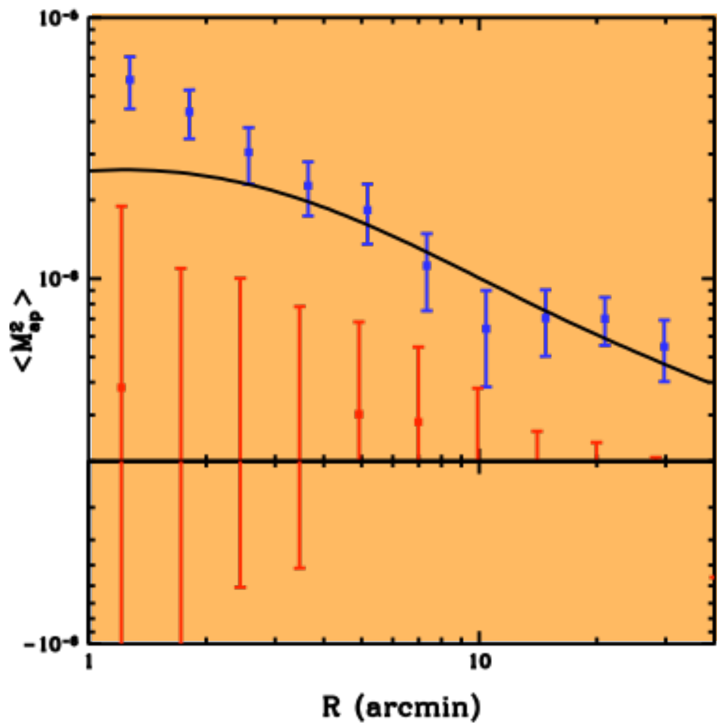
Zhang et al. 2007:
The ratio of the
galaxy-shear correlation function
to the
galaxy-velocity correlation function
is a clean test of the equivalence of two potentials that appear in the perturbed GR metric.

Different lines on this plot are various alternative gravity theories.

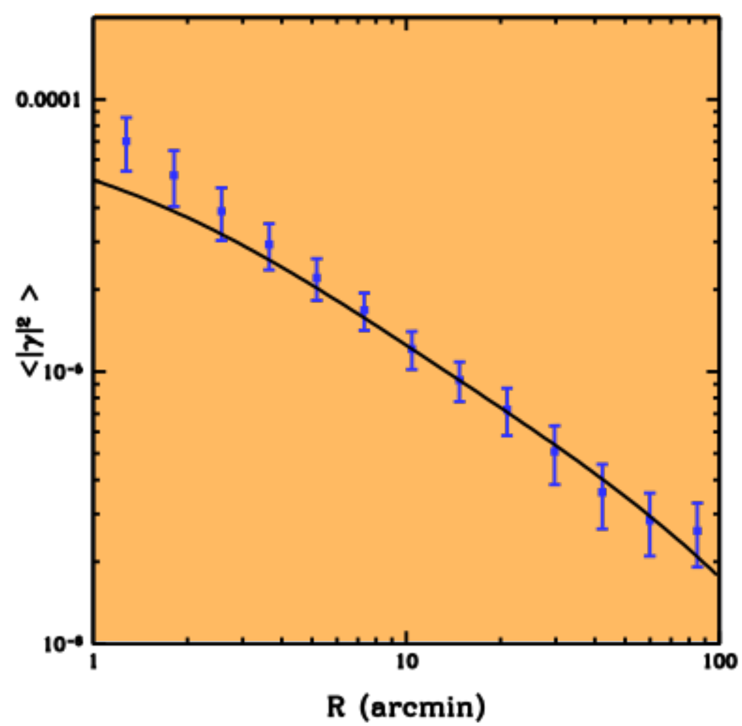
Points and error bars show value and uncertainties from combined WL and BAO surveys in a LCDM Universe



Data from Jarvis et al (2005), 75-square-degree CTIO Lensing survey



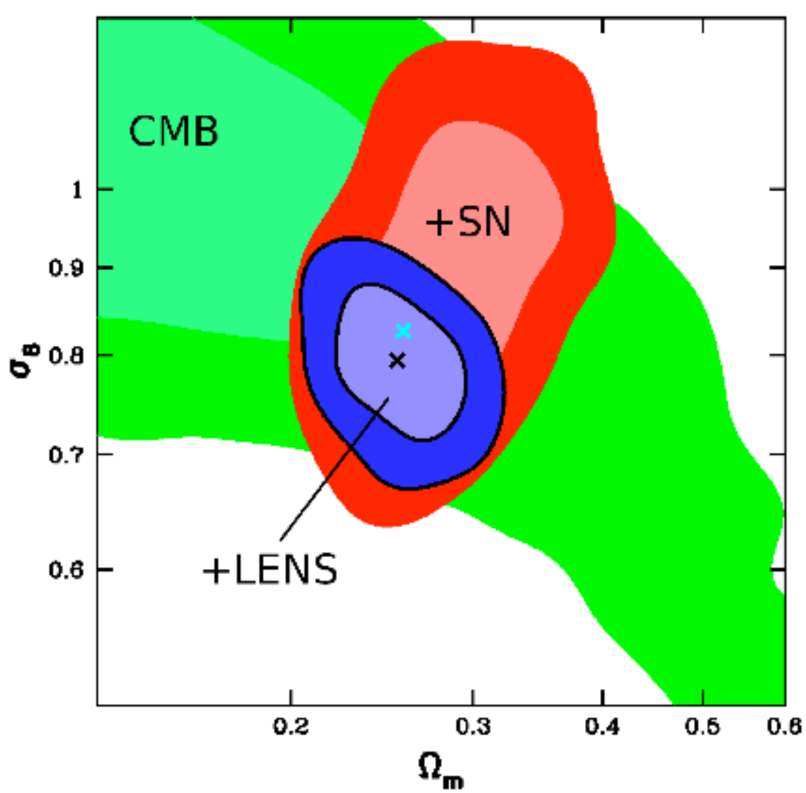
Shear "aperture mass" (=power spectrum)

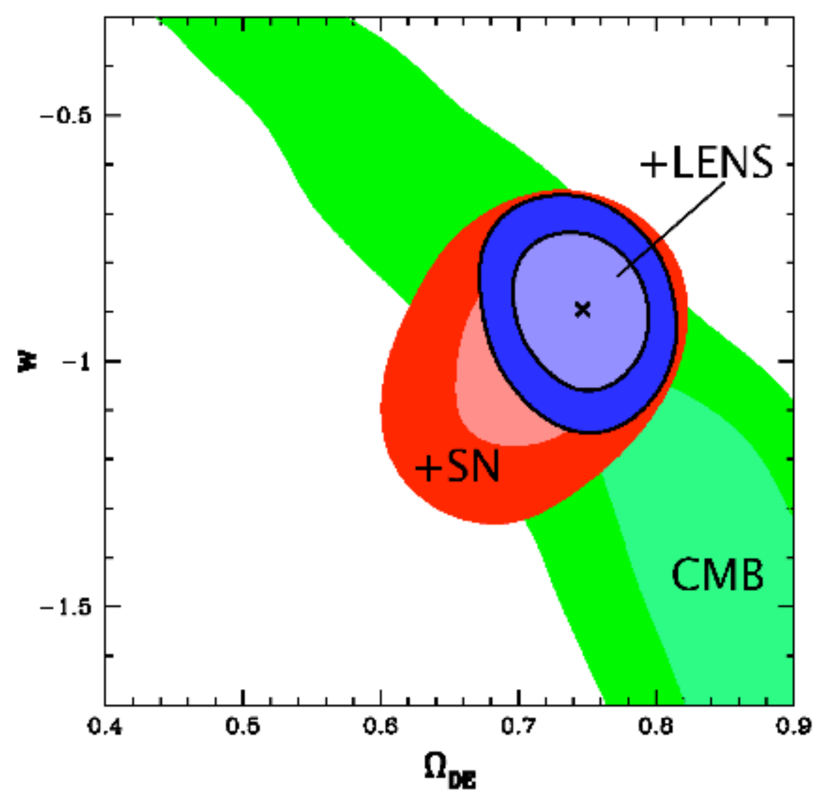


Shear correlation function

(using ~2 million galaxies)

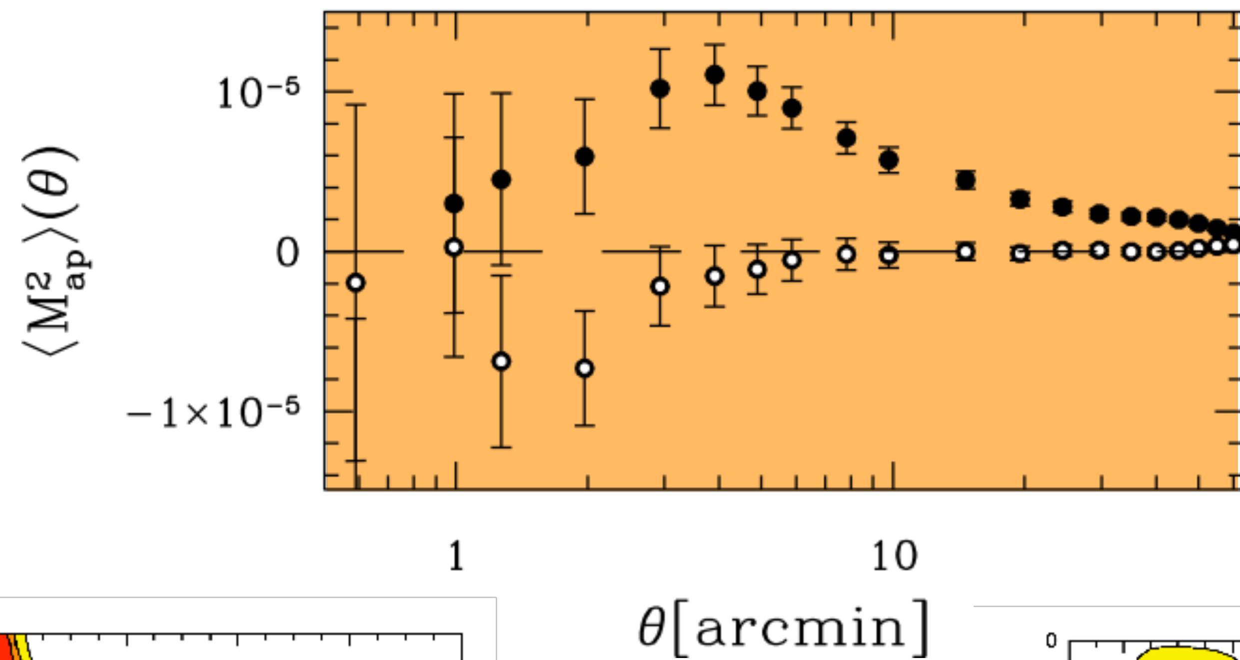
Real lensing dark-energy measurements:

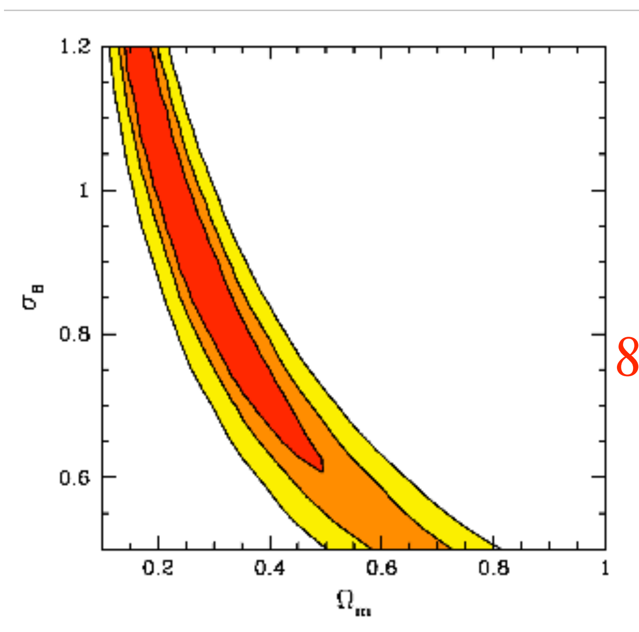




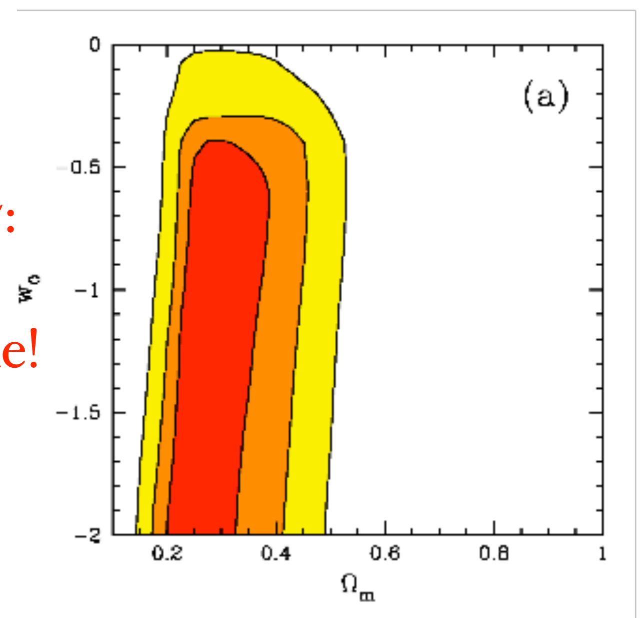
Results for constant-w models from Jarvis, Jain, & Bernstein (2005) from the 75-square-degree CTIO lensing survey

Initial Data from the CFH Legacy Survey





Hoekstra et al 2005:
22 square degrees,
8x more data to come!

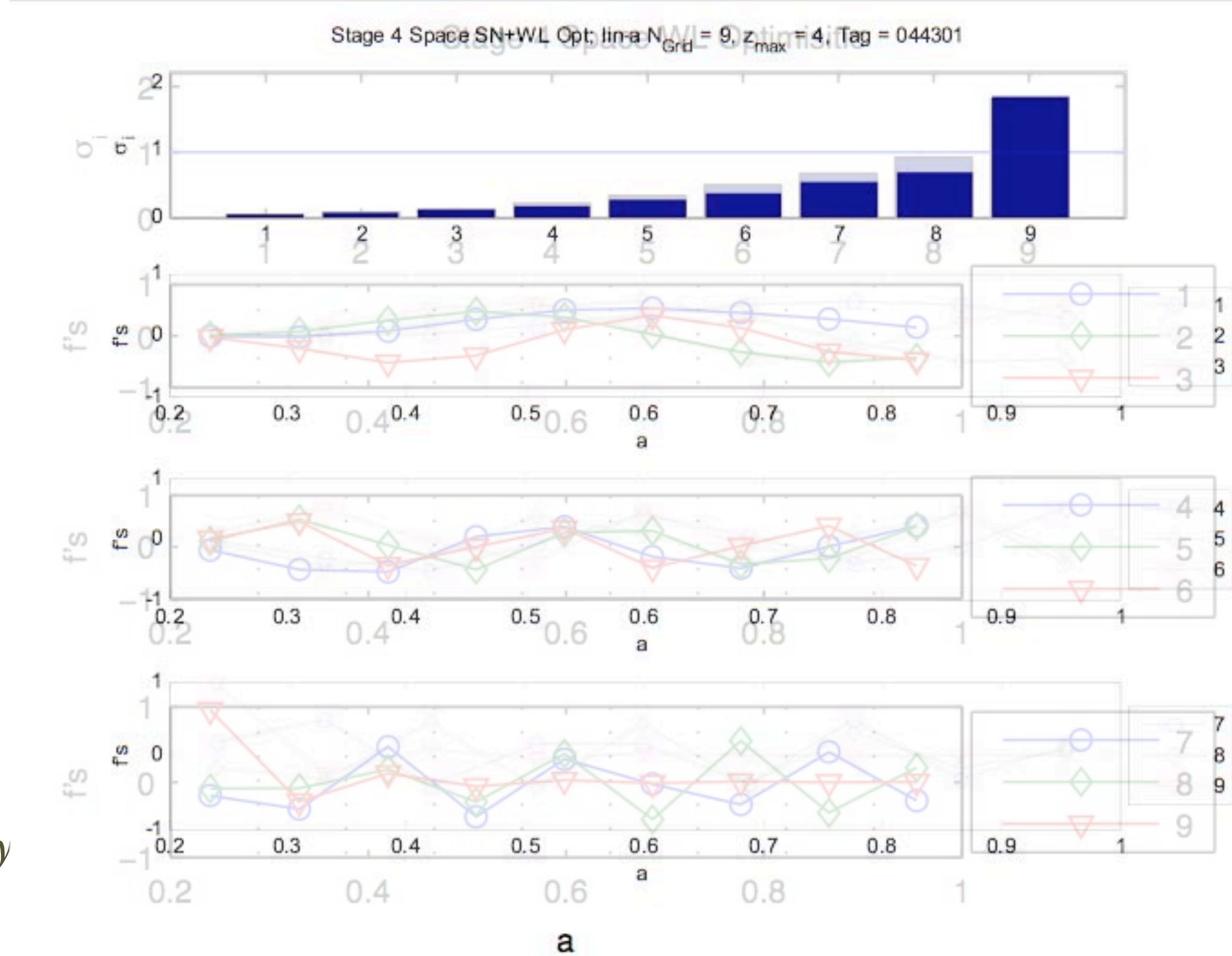


Weak lensing experiments (cf. D. Wittman)

- Present: CFH Legacy Survey, 170 square degrees multi-color ground-based visible data. *(tens of millions of galaxies)*
- Nearer-term ground-based visible surveys *(hundreds of millions)*:
  - *Kilo-degree Survey* (KIDS), 1500 square degrees
  - *Dark Energy Survey* (DES): 5000 square degrees.
  - *Pan-STARRS*: TBD
- Long-term proposals *(billions of source galaxies)*:
  - The *Large Synoptic Survey Telescope (LSST)*: ground-based 8-meter with 3.5 degree FOV, 2 Gpix camera. Deep multicolor data over >20,000 square degrees
  - *Supernova Acceleration Probe (SNAP)*: 4000 square degrees space-based visible+NIR imaging + redshift survey (also *Destiny*)
  - *Dark Universe Explorer (DUNE)*: mix of ground+space vis/NIR?
  - *Square Kilometer Array:* Nearly-full-sky 21-cm survey.
  - Lensing of the CMB and reionization-epoch radiation?

Dark-energy constraints of the future:

- Describe w(a) as a stepwise function.
- Express constraints as a series of eigenfunctions
- About 2 eigenfunctions constrained to <0.5 accuracy when current experiments are complete.
- A. Albrecht with GMB, extension of *Dark Energy Task Force* work.



Extensive non-parametric constraints on DE with additional future data.

Conclusions

- **Weak gravitational lensing** is a conceptually simple, theoretically calculable measure of many potential "new physics" phenomena on the dark side.
- The rich variety of statistics extractable from the WL sky can distinguish different kinds of new physics as well as most expected systematic errors.
- WL is currently making <10% measures of cosmological quantities over <200 square degrees. Proposals to scale up by 100x from ground and space:
  - Hardware efforts are quite feasible.
  - Significant room for advance in WL methodologies and theory.
- Expect order-of-magnitude improvements in each dark-energy equation of state parameter, part-per-thousand limits on curvature, and differentiation between alternative gravity theories.
- Once the full available sky is mapped, it's not clear what else we could learn about the acceleration phenomenon!